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Power Systems in Future Spacecraft**

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# Insulation Requirements of High-Voltage Power Systems in Future Spacecraft

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## Summary

The scope, size, and capability of the nation's space-based activities are limited by the level of electrical power available. Long-term projections show that there will be an increasing demand for electrical power in future spacecraft programs. The level of power that can be generated, conditioned, transmitted, and used will have to be considerably increased to satisfy these needs, and increased power levels will require that transmission voltages also be increased to minimize weight and resistive losses.

At these projected voltages, power systems will not operate satisfactorily without the proper electrical insulation. Open or encapsulated power supplies are currently used to keep the volume and weight of space power systems low and to protect them from natural and induced environmental hazards. Circuits with open packaging are free to attain the pressure of the outer environment, whereas encapsulated circuits are imbedded in insulating materials, which are usually solids, but could be liquids or gases. Up to now, solid insulation has usually been chosen for space power systems.

If the use of solid insulation is continued, when voltages increase, the amount of insulation for encapsulation also will have to increase. This increased insulation will increase weight and reduce system reliability. Therefore, nonsolid insulation media must be examined to satisfy future spacecraft power and voltage demands. In this report, we assess the suitability of liquid, space vacuum, and gas insulation for space power systems.

## Introduction

Spacecraft power systems have continuously increased output from a few watts in the 1960's to several kilowatts in the 1990's. With the development of advanced payloads for future space missions, such as the space station and space manufacturing, we estimate that electrical loads will be in multiples of kilowatts. Communication satellites using trans-

mission frequencies in the gigahertz range are equipped with traveling-wave tubes that need high-voltage sources with increased power capacity. Recent space-borne radar systems for Earth observation and meteorological studies operate with pulsed traveling-wave tube amplifiers at voltages exceeding 15 kV (refs. 1 and 2). Long-term projections for space activities point to increasing demand for higher power in the coming decades (refs. 3 and 4).

Larger spacecraft with increased power requirements will require longer cable runs. Their electrical transmission and distribution systems will assume greater similarity to the compact electric utility systems used on Earth. Therefore, it will become necessary to increase voltage levels for power distribution to decrease currents, resulting in lighter conductors and reduced losses. Increasing the voltage to 10's of kilovolts will require the development of new concepts for distribution, protection, and control systems for spacecraft.

The local environment surrounding spacecraft has been extensively studied (refs. 5 to 8). Features of this environment are responsible for most problems in spacecraft electrical systems. Phenomena such as outgassing, effluent gases, radiation, space particulates, solar winds and solar flares, and plasma interactions dictate that high-voltage equipment and systems designers take natural and induced environmental effects into consideration (ref. 9). Significant environmental features are vacuum pressure, temperature, electromagnetic radiation, cosmic radiation, atomic and molecular gases, plasmas containing ions, protons, electrons, meteoroids, particles, and debris.

The induced environment includes both self-induced phenomena, such as spacecraft outgassing and effluents, and externally induced phenomena, namely, radiated fields and electromagnetic pulses. High-voltage equipment and cables must be shielded both physically and electromagnetically to prevent coupling of high-voltage pulses and transients into low-voltage circuitry on board the spacecraft (ref. 3).

There are additional constraints, such as lifting capability, weight, and volume. The need for compact packaging, while maintaining electrical system integrity during missions of several years duration, is of primary importance.

With higher voltage equipment and large configurations, new design techniques that account for the environment must be considered. Problems due to interactions of high-voltage

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components with the space environment will take on increased significance. Space plasma, outgassing, unburned residue, and pressure due to gas leakage will affect exposed conductors and cables. Obvious options are either to have open construction that will be exposed to the surrounding environment or to enclose the power supply system in solid, liquid, or gas insulation.

The ideal insulation for higher voltage systems in aerospace applications should be light, chemically stable, and a good corona suppressor. It should withstand high voltages, have low dielectric loss, and have good thermal conductivity. If possible, it should be self-healing in case of electrical discharges. In this report, we compare the merits of solid, liquid, space vacuum, and gas insulation for space electrical power systems.

## Liquid Insulation

Liquid insulating materials offer reasonable alternatives for many terrestrial applications and are widely used in ground-based power systems. However, for applications in aerospace systems, they suffer from disadvantages such as high weight and cost, low operating temperature limits, and the need for containers that seal properly. During longer missions, micrometeoroids could damage the container and the power system could fail because of liquid leakage. Therefore, a replenishing supply of the liquid insulation would be needed. In addition, escaped liquid could contaminate other sensitive equipment, such as optical lenses, and the insulation could deteriorate because of chemical decomposition due to temperature, aging, and partial discharges. Another disadvantage is the possibility of reaction with contact materials, resulting in the evolution of moisture and gases or the formation of corrosive byproducts. Chemical deterioration is accompanied by increased dielectric losses and reduced dielectric strength.

The most serious problem with liquid insulation is its potential for forming bubbles, which in the microgravitational environment may remain attached to the electrodes or lodge within the high-voltage circuits between electrodes (ref. 10). Dielectric inhomogeneities and boundaries between media that have different dielectric constants cause abrupt changes in electric field strength. The resulting enhancement of the field strength may either cause immediate spark breakdown of the liquid insulation or may result in a gradual deterioration due to partial discharges. Therefore, liquid insulation should not be considered for use in aerospace systems.

## Solid Insulation

Early experience with the design of power supplies resulted in the general recommendation that high-voltage power supplies be completely encapsulated (refs. 11 to 13).

Widely used in the present spacecraft power supplies, solid insulation has inherent disadvantages that become more pronounced as voltage requirements increase. As voltages are increased, solid insulation becomes more voluminous, resulting in increased mass and reduced reliability because it is more difficult to obtain void-free and uniform encapsulated systems and components. Manufacturing and molding of encapsulating materials into larger volumes will increase cost and internal stresses.

Exposure to radiation, thermal stresses, and aging can crack the insulation between high-voltage electrodes and other electric parts. Material incompatibility will result in poor or no bonding between parts or circuits. The use of inferior or deteriorated insulation or of insulation with flaws (such as discontinuities and impurities, which can occur even in high-quality insulation) will shorten life and eventually cause failure. A hole or crack in the insulation, across which a high voltage exists, may cause repeated electrical discharges. These will ultimately carbonize a conductive path and cause the insulation to fail.

For higher operating voltages, longer life, and larger space structures, the effects of micrometeoroids and plasma on dielectrics must be considered. Micrometeoroids are 0.1- to 80- $\mu$ m-diameter dust, metallic, or insulation particles; 0.1- to 5- $\mu$ m-diameter particulates from rocket exhaust compounds, primarily carbon compounds and aluminum oxide; and cosmic dust composed primarily of Fe, Ni, Mg, Na, Ca, Cr, H, O, and Mn.

The impact velocities of micrometeoroids range between 20 and 30 km/s (ref. 8). Upon impact, the particle usually vaporizes, producing plasma and a crater. Some particle elements may penetrate through the spacecraft materials, resulting in erosion, debris, and charge production due to shock-induced ionization. This enhances the surface flashover of exposed insulation, which can eventually destroy the insulators.

There is no single preferred insulating material. The electrical parameters and quality of the insulation depend upon, among other things, the circuit and its parts to be protected, as well as the cleaning, processing, and handling of the material. Successfully used in systems up to now, solid insulation loses its attractiveness for higher voltages because of these disadvantages.

## Space Vacuum as Electrical Insulation

Laboratory-generated vacuum has excellent dielectric properties because of the absence of conductive or ionizable media. Its electrical properties are determined by the electrode and insulator surfaces, and breakdown is primarily the result of surface phenomena. Surface flashover in a vacuum occurs along the surface of solid dielectrics used as spacers or to encapsulate components and systems. High-quality vacuum that involves a tank with a vacuum pump (such as

used in laboratories) has been suggested for aerospace use (ref. 14). However, this approach will substantially increase the weight of the system.

Space vacuum would be the obvious choice if it were not contaminated with a wide variety of particles and ions. In space power systems, surface discharges are a common occurrence. Volume breakdown may occur because the space vacuum is contaminated with gas. This is the main cause of its reduced breakdown strength.

The interaction of spacecraft with surrounding plasma charges the vehicle assemblies and exposes the electrical components to thousands of volts, resulting in arcing and possible breakdown of the exposed insulation. Such problems have been observed on some spacecraft and are suspected as the source of anomalies on numerous other vehicles (ref. 15).

Spacecraft and electronic component outgassing products have historically been the source of many high-voltage component failures. These gases tend to pressurize internal spacecraft cavities and the immediate spacecraft environment, to further plague the spacecraft high-voltage designs.

There are suggestions in the literature that an open construction, where space vacuum is part of the high-voltage insulation, would have certain advantages over solid insulation at voltages of about 15 kV (ref. 16). Open construction was used in the Communication Technology Satellite (CTS) in the 1970's (ref. 17). The major advantage is that space vacuum is the lowest weight insulation. In addition, space vacuum systems can be assembled, tested, and repaired with relative ease, since all parts are accessible. Space vacuum insulation does not involve manufacturing and is not susceptible to aging. In the event of partial discharges or flashover, space vacuum is self-restoring.

However, vacuum chamber testing of high-voltage components that were later used in the Space Power Experiments Aboard Rockets (SPEAR) project showed that, in the presence of weak magnetic fields and high-voltage anodes, severe breakdown occurred even at very low pressure (ref. 18). This confirmed the analytical and computational work by Kundhardt et al. (ref. 19) and Katz et al. (ref. 20), and the theoretical breakdown and discharge behavior between two surfaces in the presence of magnetic fields (ref. 21).

Certain aspects of the theory of electrical breakdown in gases apply to space vacuum because of its imperfect nature. Next, we briefly describe the phenomenon of electrical breakdown in gases and the resulting Paschen's law.

Townsend (ref. 22) observed that the current through a uniform-field air gap at first increases proportionately with applied voltage in the region  $(0-V_1)$ , then remains nearly constant at a plateau value  $I_0$  (fig. 1). The current  $I_0$  corresponds to the photoelectric current produced at the cathode by external radiation. At voltages higher than  $V_2$ , the current rises above  $I_0$  at a much higher rate with increasing voltage until a spark results. If the illumination level at the cathode is

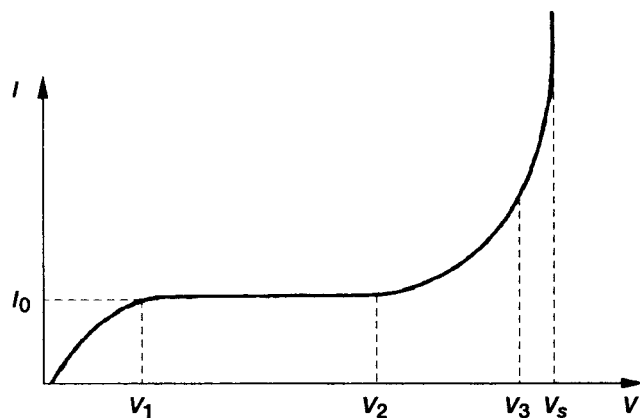


Figure 1.—Current growth as a function of applied voltage to a parallel plane gap in gases.

increased, the plateau  $I_0$  rises proportionately, but the voltage  $V_s$  at which sparking occurs remains unaltered if there is no space-charge distortion of the electric field between the electrodes. The increase of current in the region  $V_2-V_3$  is ascribed to ionization by electron impact. As the electric field increases, electrons leaving the cathode are accelerated between collisions, until they gain enough energy to cause ionization on collision with gas molecules or atoms. The secondary process accounts for the sharper increase of the current in the region  $V_3-V_s$  and the eventual spark breakdown of the gap.

To explain this, Townsend introduced a quantity  $\alpha$ , known as Townsend's first ionization coefficient. It is defined as the number of electrons produced by an electron per unit length of path in the direction of the field. If  $n$  is the number of electrons per second reaching a distance  $x$  from the cathode in the field direction, the increase  $dn$  in an additional distance  $dx$  is given as

$$dn = \alpha n dx$$

Integration over distance  $d$  between the cathode and the anode results in

$$n_a = n_0 e^{\alpha d} \quad (1)$$

Here,  $n_0$  is the number of primary electrons generated per second at the cathode and  $n_a$  is the number of electrons arriving at the anode per second. In terms of current, with  $I_0$  as the current leaving the cathode, equation (1) becomes

$$I = I_0 e^{\alpha d} \quad (2)$$

The term  $e^{\alpha d}$  is called the electron avalanche, which represents the number of electrons produced by one electron in traveling the distance from the cathode to the anode.

The process of electron attachment from an ionized gas (by any of the several processes described later) may be expressed by a relation similar to equation (1), which defines electron multiplication in a gas. If  $\eta$  is the attachment coefficient defined (by analogy with the ionization coefficient  $\alpha$ ) as the number of attachments produced in the path of a single electron traveling a unit distance in the direction of the electric field, then

$$dI = -\eta I dx$$

With electron current  $I_0$  starting at the cathode and with electrode spacing  $d$ , the current  $I$  at the anode is obtained as

$$I = I_0 e^{-\eta d} \quad (3)$$

If electron generation by collision and electron loss by attachment operate simultaneously, then the resulting number of free electrons is given as

$$dn = n(\alpha - \eta) dx$$

The number of electrons at a distance  $x$  from the cathode in the field direction is obtained by integrating the preceding equation from  $x = 0$ , with  $n_0$  electrons starting from the cathode. The result is

$$n = n_0 e^{(\alpha - \eta)x} \quad (4)$$

The steady-state current consists of two components, one resulting from the flow of electrons and the other from the negative ions. To determine the total current under such conditions, we must find the negative component of the current. The increase in negative ions over a distance  $dx$  is given by

$$dn_- = n\eta dx = n_0\eta e^{(\alpha - \eta)x} dx$$

Integration from 0 to  $x$  leads to

$$n_- = \frac{n_0\eta}{\alpha - \eta} [e^{(\alpha - \eta)d} - 1] \quad (5)$$

The total current is the sum of the two components given by equations (4) and (5):

$$\frac{n + n_-}{n_0} = \frac{\alpha}{\alpha - \eta} e^{(\alpha - \eta)d} - \frac{\eta}{\alpha - \eta} \quad (6)$$

The expression for the current becomes

$$I = I_0 \left[ \frac{\alpha}{\alpha - \eta} e^{(\alpha - \eta)d} - \frac{\eta}{\alpha - \eta} \right] \quad (7)$$

In the absence of attachments,  $\eta = 0$ , and equation (7) reduces to equation (2).

According to equation (2), a graph of  $\log I$  against the gap length  $d$  should give a straight line of slope  $\alpha$  for a given gas pressure  $p$ , if the field strength  $E$  is kept constant. Measurements of current between parallel plane electrodes showed that, at higher voltages, the current  $I$  increases at a more rapid rate than given by equations (2) or (7). Figure 2 shows typical behavior obtained by plotting  $\log I$  versus electrode separation  $d$  at constant pressure.

To explain this behavior, Townsend postulated that a second mechanism must be affecting the current. He first considered liberation of electrons in gas by collision of positive ions, and later considered liberation of electrons from the cathode by positive ion bombardment. Other processes responsible for the deviation of the figure 2 curves of  $\log I$  versus  $d$  include secondary electron emission at the cathode by photon impact and photoionization of the gas itself.

Let  $n_a$  be the number of electrons reaching the anode per second,  $n_0$  the number of electrons emitted from the cathode by, say, ultraviolet illumination,  $n_+$  the number of electrons released from the cathode by positive ion bombardment, and  $\gamma$  the number of electrons released from the cathode per incident ion, also known as the secondary ionization coefficient. Then,

$$n_a = (n_0 + n_+) e^{\alpha d}$$

and

$$n_+ = \gamma [n_a - (n_0 + n_+)]$$

Eliminating  $n_+$  leads to

$$n_a = \frac{n_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$

The expression for the steady-state current follows as

$$I = I_0 \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \quad (8)$$

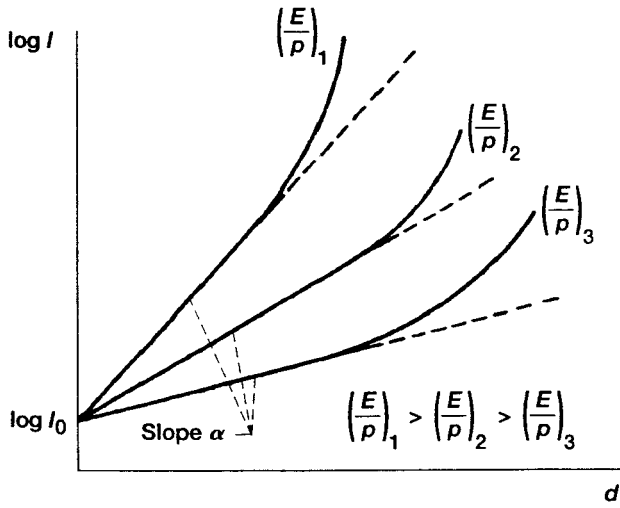


Figure 2.—Gap current as a function of electrode spacing in uniform field gaps.

As the voltage between the electrodes in a gas with small or negligible electron attachment increases, the electrode current at the anode increases in accordance with equation (8).

It has been experimentally confirmed (ref. 23) that the ionization coefficient  $\alpha$ , the gas pressure  $p$ , and the electric field intensity  $E$  are related as

$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right) \quad (9)$$

By introducing equation (9) and  $E = V/d$  in equation (8), we get

$$I = I_0 \frac{e^{pd \cdot f\left(\frac{V}{pd}\right)}}{1 - \gamma \left[ e^{pd \cdot f\left(\frac{V}{pd}\right)} - 1 \right]} \quad (10)$$

With increasing  $V$ , a point is reached when there is a transition from the dark current  $I_0$  to a self-sustaining discharge. At this point  $I$  becomes indeterminate, and the denominator in equation (8) vanishes; that is,

$$\gamma(e^{\alpha d} - 1) = 1 \quad (11)$$

If electron attachment is taken into account, then equation (11) becomes

$$\frac{\gamma\alpha}{\alpha - \eta} [e^{(\alpha - \eta)d} - 1] = 1 \quad (12)$$

or

$$\gamma e^{(\alpha - \eta)d} = \gamma e^{\alpha d} \approx 1 \quad (13)$$

where  $\bar{\alpha} = \alpha - \eta$  represents the effective ionization coefficient,  $e^{\bar{\alpha}d} \gg 1$ , and  $\alpha \gg \eta$ .

The electron current at the anode equals the current in the circuit. Theoretically, this current becomes infinitely large, but in practice it is limited by the external circuit and, to a lesser extent, by the voltage drop in the arc.

The spark criterion of equation (12) also can be expressed as

$$\bar{\alpha}d = \ln\left(\frac{1}{\gamma} + 1\right) = K \quad (14)$$

Equation (12), which defines the condition for the spark onset, is called the Townsend's breakdown criterion. For  $\gamma(e^{\bar{\alpha}d} - 1) = 1$ , the discharge due to the ionization process is self-sustaining and can continue in the absence of  $I_0$ , so that the criterion  $\gamma(e^{\bar{\alpha}d} - 1) = 1$  defines the sparking threshold. For  $\gamma(e^{\bar{\alpha}d} - 1) > 1$ , the ionization produced by successive avalanches is cumulative. The spark discharge grows more rapidly the more  $\gamma(e^{\bar{\alpha}d} - 1)$  exceeds unity. For  $\gamma(e^{\bar{\alpha}d} - 1) < 1$ , the current  $I$  is not self-sustained, and it ceases to flow when the source providing the primary current  $I_0$  is removed.

In the Townsend's criterion of equation (12), we express the ionization coefficient  $\bar{\alpha}/p$  as function of field strength and gas pressure, in accordance with equation (9); that is,

$$\frac{\bar{\alpha}}{p} = f\left(\frac{E}{p}\right)$$

We then get

$$e^{f\left(\frac{E}{p}\right) \cdot pd} = \frac{1}{\gamma} + 1 \quad (15a)$$

or

$$f\left(\frac{E}{p}\right) \cdot pd = \ln\left(\frac{1}{\gamma} + 1\right) = K \quad (15b)$$

For a uniform field,  $V_b = Ed$ , where  $V_b$  is the breakdown voltage,

$$e^{f\left(\frac{V_b}{pd}\right) \cdot pd} = K \quad (16a)$$

or

$$V_b = f(pd) \quad (16b)$$

which means that the breakdown voltage  $V_b$  of a uniform field gap is a unique function of the product  $pd$ . Equation (16) is known as the Paschen breakdown law. The relation between the sparking voltage and  $pd$ , the product of gas pressure  $p$  and electrode separation  $d$ , is given in figure 3. The breakdown voltage goes through a minimum value  $(V_b)_{\min}$  at a particular value of the product  $(pd)_{\min}$ .

This implies that if the mean free path of the electrons is sufficiently long, then an avalanche of ionizations can occur as the electrons collide with neutral particles to create an ionized, conducting path between the electrodes, resulting in an arc. If the pressure or distance is excessive, the electrons between the plates will only interact locally as a result of the applied voltage. If the pressure is too low, no ionization of the neutral gas particles can take place.

As pressure increases, the density of the gas increases. Therefore, with the separation  $d$  remaining constant, higher electric field strength is required to accelerate electrons over the mean free path and ionize the gas molecules on collision. The same phenomenon will result if the pressure  $p$  is kept constant and the separation  $d$  is increased. If the pressure and/or the distance are decreased, the breakdown voltage will decrease. At a certain value of  $pd$ , the breakdown voltage reaches its minimum. It rises again when the pressure is reduced below this minimum. The Paschen curve is only applicable to parallel plane electrodes or uniform electric fields in the absence of a magnetic field.

Townsend's argument can be extended to nonuniform field situations (ref. 24), where the number of electrons at the anode  $n$  can be compared with the initial electrons at the cathode  $n_0$  as

$$n = n_0 \frac{1 + \int_0^d \exp \left[ \int_0^x (\alpha - \eta) dx \right] \alpha dx}{1 - \gamma \int_0^d \exp \left[ \int_0^x (\alpha - \eta) (dx) \right] \alpha dx} \quad (17)$$

Thus, the Townsend criterion for breakdown in nonuniform field gaps is derived from equation (17) as

$$\gamma \int_0^d \exp \left[ \int_0^x (\alpha - \eta) dx \right] \alpha dx = 1 \quad (18)$$

For uniform field gaps, equation (18) reduces to

$$\frac{\gamma \alpha}{\alpha - \eta} [e^{(\alpha - \eta)d} - 1] = 1 \quad (19)$$

which is the same as equation (12).

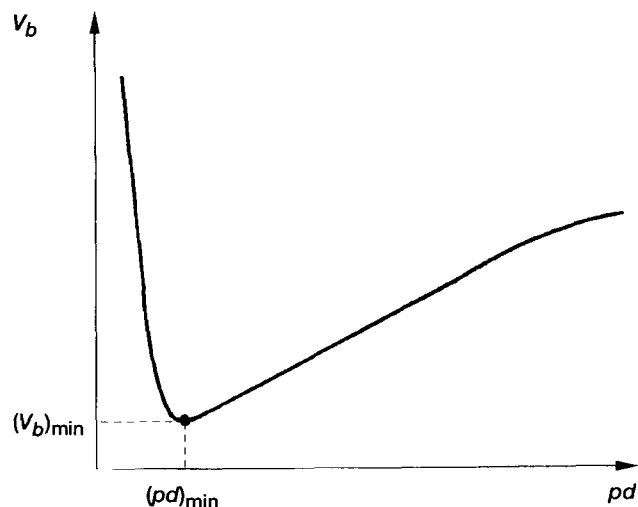


Figure 3.—Breakdown voltage as a function of the product of pressure  $p$  and electrode spacing  $d$ .

The Townsend criterion of equation (18) or (19) is of little use to an engineer because the secondary ionization coefficient  $\gamma$  is a very sensitive function of the electrode surface condition and the degree of gas purity. Measurements of  $\gamma$  have so far been made only at pressures below 3.4 kPa (ref. 24), and these values are not valid for higher, but technically important, gas pressures.

In the "streamer mechanism" it is assumed that the growth of a single electron avalanche becomes unstable before reaching the anode. This instability results in the formation of fast-moving streamers from the avalanche head, which form a highly conducting channel across the gap, resulting ultimately in the collapse of the applied voltage. The basic mechanism behind the formation of these streamers is assumed to be photoionization in the gas. Though a satisfactory quantitative theory for streamer formation has not been formulated, Meek (ref. 25) developed the following criterion for streamer formation in nonuniform field gaps:

$$(\alpha - \eta)_x \exp \left[ \int_0^x (\alpha - \eta) dx \right] = K_1 E_x \sqrt{\frac{x}{p}} \quad (20)$$

Here,  $x$  denotes the distance from the cathode as the avalanche length at the moment when streamers are formed. The quantity  $(\alpha - \eta)_x$  is the effective Townsend first ionization coefficient at the avalanche head,  $p$  is gas pressure, and  $K_1$  is a constant. A similar relation was proposed independently by Raether (ref. 26), who suggested that a critical number ( $10^8$ ) of charge carriers is necessary to transform an avalanche into a streamer. Meek's equation was modified by Pedersen (refs. 27 and 28) to obtain the following streamer criterion:

$$\int_0^{x_c} (\alpha - \eta) dx = K \quad (21)$$

Here  $x_c$  is the critical avalanche length which is the distance between the highly stressed electrode and the point in the electrode gap where  $\alpha = \eta$  and  $K$  is a constant. The limiting case of the streamer criterion is obtained by setting  $K = 0$  in equation (21), this gives

$$\int_0^{x_c} (\alpha - \eta) dx = 0 \quad (22)$$

Thus, the limiting value of the breakdown strength in a gas is obtained by setting

$$\alpha = \eta \quad (23)$$

Equation (23), which sets the threshold condition for growth of electron avalanches, is satisfied at a limiting value of the field intensity, called the critical field intensity. At normal temperature and pressure, its values are 89.5 and 29 kV/cm for sulphur hexafluoride (SF<sub>6</sub>) and air, respectively. For  $\alpha < \eta$ , an electron avalanche will not grow in an electronegative gas. In practical cases, electron avalanches will grow when  $\alpha$  is slightly greater than  $\eta$ .

The Paschen minimum and its vicinity are important in an imperfect vacuum. Table I lists the minimum Paschen breakdown voltages for several gases (ref. 29). Favorable conditions for low-voltage breakdown are easily achieved in space vacuum encountered in low-Earth orbits (LEO's) and even in regions of high altitude. The LEO environment is a low-density gas or plasma permeated by a magnetic field. Spacecraft charging can reach as high as 1.4 kV at altitudes as low as 800 km (ref. 30). The ion concentration in this region (NO<sup>+</sup>, O<sub>2</sub><sup>+</sup>, and water vapor) reaches up to 10<sup>5</sup>/cm<sup>3</sup>, with electron densities of approximately the same order of magnitude (refs. 31 and 32). Such LEO flights are affected by significant spacecraft charging (ref. 33). In these situations, Paschen breakdown can take place at relatively low voltages. In space flights of short duration, from a few minutes to a few days, such as the space shuttle, the ambient pressure inside the spacecraft retains a critical level, which is not far from the pressure at which the minimum of the Paschen breakdown voltage can occur. Thus, high-voltage equipment will not operate reliably in a vacuum in this environment.

Earth observation and communications missions in the upper terrestrial environment have durations of months and years. The range of altitudes can vary from 400 to 36 000 km. Although ion and electron densities decrease with altitude, galactic cosmic radiation and trapped radiation assume significant orders of magnitude.

TABLE I.—MINIMUM BREAKDOWN VOLTAGES FOR VARIOUS GASES

Gas	Paschen minimum breakdown voltage, (V <sub>b</sub> ) <sub>min</sub> , V	Product of gas pressure and electron separation, <i>pd</i> , at (V <sub>b</sub> ) <sub>min</sub> , Pa·m
Air	327	0.754
Argon	137	1.197
Hydrogen	273	1.53
Helium	156	.532
Carbon dioxide	420	.678
Nitrogen	251	.891
Nitrous oxide	418	.665
Oxygen	450	.931
Sulfur dioxide	457	.439
Hydrogen sulfide	414	.798
Tetrafluoromethane	420	1.0
Sulfur hexafluoride	520	1.0

An open construction in this environment may be exposed to uncontrolled discharges and flashover behavior. It is also more susceptible to micrometeoroid damage than encapsulated systems are. Although the quality of vacuum is relatively clean, details of the effects of radiation, particle flow, and atmospheric conditions relative to solar and space location are not known. These concerns indicate that the intrinsic properties of the space vacuum render it unsuitable as an insulating medium for high voltages (ref. 34).

## Gases as Space Insulation

Certain gases have excellent dielectric properties for electrical insulation and are successfully being used in terrestrial power systems. In the past, they had not been seriously considered for space applications because of certain disadvantages, namely, the container weight and possible leakage. However, compressed gases become more attractive in comparison to solid insulation and space vacuum as voltages and power are increased, and their use in future spacecraft power systems cannot be ruled out (ref. 8). Designs already exist for SF<sub>6</sub>-insulated transmission lines to be used in high-power spacecraft (ref. 8).

Like liquid insulation, gas insulation requires a pressure vessel container. Because of the potential for gas leakage, a reserve container with gas will be needed during prolonged missions, adding weight. The pressure vessels will adequately shield the gas insulation and electronics components from space radiation, contaminants and micrometeoroids, and external electromagnetic interference.

The influence of effluents, and outgassing from the electric circuit and the gas container, will be eliminated if compressed gases are used. Unlike solids or liquids, the electrical properties of many gases are not adversely affected by small



amounts of gaseous impurities (refs. 24 and 35 to 37). Thermal stresses can be minimized if the gas has superior heat exchange properties. Aging problems will depend on the gas insulation's chemical stability, moisture content, and the degree of partial discharges.

The electric field strength is an important parameter in determining the integrity of an electric system. Commercial electrical equipment can be designed with the average field stress of 5 to 20 V/mil within the electrical insulation. Current aerospace designs use electric stress averages between 50 to 200 V/mil for solid insulation. This figure can be raised substantially for certain gases.

Gases have lower weight than solid and liquid insulation. In addition, equipment can be reduced in size if the dielectric strength of the insulating medium is increased. The volume of a system insulated with certain gases could be as low as one-third of that using solid insulation rated for the same voltage and power. Gases do not suffer from voids or cracks, which in solids can be introduced during manufacture or develop during the aging process.

Generally, the breakdown strength of gases rises as their molecular weight increases. The maximum dielectric strength that can be achieved in a gas at a certain temperature is limited by its vapor pressure, and it increases with temperature.

Certain gases, including those belonging to the seventh group of the periodic table (e.g., fluorine,  $F_2$ , and chlorine,  $Cl_2$ ) and those containing halogen atoms (e.g., sulfur hexafluoride,  $SF_6$ ; dichlorodifluoromethane,  $CCl_2F_2$ ; perfluoropropane,  $C_3F_8$ ; perfluorobutane,  $C_4F_{10}$ ; hexafluoroethane,  $C_2F_6$ ; and tetrafluoromethane,  $CF_4$ ) are known to have considerably higher dielectric strength in comparison to air under similar conditions. Their high breakdown strength depends mainly on their ability to take up free electrons, thereby forming heavy negative ions. Gases having this property are called electronegative.

## Sulfur Hexafluoride

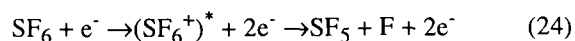
Not all electronegative gases are suitable for use as dielectrics. Some such gases have very low breakdown strength. Of the many available electronegative gases,  $SF_6$ , especially, has gained importance as electrical insulation. On Earth, it is the most commonly used gas in high-voltage, gas-insulated electrical equipment (such as cables, compact switchgear, substations, and circuit breakers that can handle large amounts of energy) and other commercial high-voltage equipment. It is the most suitable gas for high-voltage power supplies in high-density packaged components and where high pressure can be advantageous.  $SF_6$  is plentiful, easy to handle, and has desirable electrical properties. In addition to its high dielectric strength, it is nontoxic, chemically and thermally stable, and possesses good heat transfer properties (ref. 24). Though  $SF_6$  is chemically inert, it may form some chemical species

or products of decomposition under excessive electric discharges in the presence of water vapor and metallic particles (ref. 38).

The dielectric strength of  $SF_6$  is sensitive to the presence of strong localized fields caused by electrode surface imperfections, and the presence of metallic particles can significantly reduce its breakdown voltage (ref. 39). This effect becomes more pronounced with increasing pressure, with increasing particle length and decreasing particle diameter in the case of cylindrical particles, and with decreasing particle density. Nonconducting particles are not usually harmful unless they have conducting powder attached; in this case, they act similar to metallic particles (ref. 40). The particles acquire charge and hover or jump between electrodes. The field nonuniformity at the particle surface results in low-voltage breakdown.

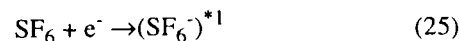
The presence of water vapor has small effect on  $SF_6$ 's breakdown voltage levels, reducing it only by 5 to 10 percent at 100-percent relative humidity. However, water vapor has a significant deleterious effect on the flashover voltage along solid insulators in  $SF_6$ . In terrestrial power systems using  $SF_6$ , humidity is limited to less than 500 ppm by volume (ref. 41). For all these reasons, the dielectric strength of  $SF_6$  achieved in practical devices is not much higher than about 50 percent of its intrinsic strength. For applications in spacecraft power systems, these degrading effects can be eliminated or substantially suppressed by removing humidity, avoiding particle entrapment during assembly, and reducing partial discharges by avoiding sharp metal points and keeping electrode surfaces smooth and clean.

Several ionization processes in  $SF_6$  have been suggested (ref. 42). The following reaction requires the lowest electron energy of 15.9 eV to ionize a gas molecule upon impact (ref. 43):



Here  $(SF_6^+)^*$  is a metastable positive ion of  $SF_6$ . Negative ions are formed when either a low-energy electron attaches itself to a neutral  $SF_6$  gas molecule, resulting in a direct attachment, or when an electron attaches to one of the constituents of the molecule after dissociation, resulting in a dissociative attachment. Studies indicate that  $SF_6^-$  and  $SF_5^-$  are the predominant ions resulting from electron collisions, exceeding other possible negative ions, such as  $F^-$ ,  $F_2^-$ ,  $SF_2^-$ ,  $SF_3^-$ , and  $SF_4^-$ , by at least a factor of 100 (refs. 44 to 46).

The formation of the majority of  $SF_6^-$  ions is initiated by the following reaction (refs. 44 and 46):



The resulting  $(SF_6^-)^{*1}$  ion is metastable with a lifetime on the order of 10  $\mu s$ . This reaction is a resonance capture process with a minimum cross-section of  $10^{-15}/cm^2$  at an electron

energy of 0.05 eV. There are several possible reactions subsequent to equation (25), which can be found in the literature (refs. 41 and 43).

These processes effectively remove a light mobile electron from the swarm and replace it with a relatively heavy, slow-moving ion, thereby influencing the growth of ionization and breakdown. The processes, therefore, suppress the electron streamers.

The streamer breakdown criterion of equation (21) can be used to determine the lowest possible voltage at which SF<sub>6</sub> breakdown occurs. Both the ionization and attachment coefficients  $\alpha$  and  $\eta$  are affected by the applied electric field. Measurements reported in the literature (refs. 47 to 51) suggest that  $\alpha/p$  and  $\eta/p$  can be approximated in the vicinity of the critical region, where  $\alpha/p = \eta/p$ , by the following relations:

$$\frac{\alpha}{p} = 23 \cdot \frac{E}{p} - 12.34 \quad (\text{kPa} \cdot \text{cm})^{-1} \quad (26)$$

$$\frac{\eta}{p} = -4 \cdot \frac{E}{p} + 11.35 \quad (\text{kPa} \cdot \text{cm})^{-1} \quad (27)$$

Therefore, the effective ionization coefficient  $\bar{\alpha}$  is expressed as

$$\frac{\bar{\alpha}}{p} = \frac{\alpha - \eta}{p} = \beta \left[ \frac{E}{p} - \left( \frac{E}{p} \right)_{\text{lim}} \right] \quad (\text{kPa} \cdot \text{cm})^{-1} \quad (28)$$

where  $\beta = 27 \text{ kV}^{-1}$  and  $(E/p)_{\text{lim}} = 877.5 \text{ V} \cdot \text{kPa}^{-1} \cdot \text{cm}^{-1}$  for pure SF<sub>6</sub>. Here  $E$  denotes the applied electric field in kV/cm, and  $p$  is the SF<sub>6</sub> pressure at 20 °C in kPa. Using equation (28) in the streamer criterion of equation (21), we get

$$\beta \left[ \int_0^{x_c} E(x) dx - p x_c \left( \frac{E}{p} \right)_{\text{lim}} \right] = K \quad (29)$$

To evaluate the left side of equation (29), we need a detailed knowledge of the electric field distribution in the gap. In a uniform field gap,  $E(x)$  is constant and  $x$  is equal to the gap length  $d$ . The breakdown voltage  $V_b$  in a uniform field gap is obtained from equation (29) as

$$V_b = Ed = \frac{K}{\beta} + \left( \frac{E}{p} \right)_{\text{lim}} \cdot pd \quad (30)$$

For uniform or nearly uniform field gaps, the streamer formation directly grows into breakdown. However, in nonuniform field gaps, this is not always the case. Here the streamers develop into a steady corona discharge at low pressures. The breakdown voltage is substantially higher

than the corona inception level. In such cases, the criterion for streamer formation corresponds to corona inception.

In nonuniform field gaps, the critical avalanche length  $x_c$  is generally a very small fraction of the total gap length  $d$ . Therefore, the electric field in the region of interest (i.e., in the vicinity of the highly stressed electrode along its axis of symmetry) can be approximated (ref. 52) by

$$E(x) = \frac{E_{\text{max}}}{\left( 1 + \frac{x}{R} \right)^2} \quad (31)$$

The quantity  $E_{\text{max}}$  is the maximum field strength in the gap (i.e., the field at the tip or sharp point of the highly stressed electrode), and

$$\frac{1}{R} = \frac{1}{2} \cdot \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (32)$$

where  $R_1$  and  $R_2$  are the radii of curvature of the highly stressed electrode in two mutually orthogonal directions. The critical avalanche length  $x_c$  can be determined from equation (31). Since  $(E/p)_{\text{lim}} = E(x_c)/p$ , the value of  $x_c$  is given by

$$x_c = R \left[ \frac{E_{\text{max}}}{\left( \frac{E}{p} \right)_{\text{lim}} \cdot p} - 1 \right] \quad (33)$$

Substituting equations (31) and (33) into equation (29) yields

$$\beta R \left[ \sqrt{E_{\text{max}}} - \sqrt{\left( \frac{E}{p} \right)_{\text{lim}} \cdot p} \right]^2 = K \quad (34)$$

Therefore, the maximum electric field strength at breakdown is given by

$$\frac{E_{\text{max}}}{p} = \left( \frac{E}{p} \right)_{\text{lim}} \cdot \left( 1 + \frac{C_1}{\sqrt{pR}} \right) \quad (35)$$

where the constant  $C_1$  is calculated from

$$C_1 = \sqrt{\frac{4K}{\beta \left( \frac{E}{p} \right)_{\text{lim}}}} \quad (36)$$

Using the field utilization factor  $u = E_{\text{av}}/E_{\text{max}}$ , where  $E_{\text{av}}$  and  $E_{\text{max}}$  are the average and maximum electric field intensities, respectively, the breakdown or discharge voltage for a nonuniform field gap insulated with SF<sub>6</sub> is expressed as

$$V_b = E_{av}d = E_{max}ud \quad (37)$$

and with  $E_{max}$  from equation (35), we get  $V_b$  as

$$V_b = \left( \frac{E}{p} \right)_{lim} \cdot upd \cdot \left( 1 + \frac{C_1}{\sqrt{pR}} \right) \quad (38)$$

Thus, equations (30) and (38) give, respectively, the minimum discharge inception voltages for uniform and nonuniform field gaps insulated with compressed SF<sub>6</sub> (ref. 52). These expressions are for electrodes with smooth surfaces. The influence of electrode surface roughness is discussed by Pedersen (refs. 53 and 54).

Rod-to-plane breakdown studies have been conducted by several researchers (refs. 55 to 57). The data show that SF<sub>6</sub> has very high breakdown voltages for both positive and negative polarities. In addition, the standard breakdown deviation for 10 separate discharges is less than 7 percent, whereas in air it may be as high as 20 percent (ref. 58).

In compressed-gas insulation systems, SF<sub>6</sub> is used at pressures of 0.4 to 0.6 MPa (approximately 4 to 6 atm). The corona-onset and breakdown voltages of pressurized SF<sub>6</sub> are substantially higher than those of many other gases for both uniform and nonuniform fields of either polarity (ref. 57). SF<sub>6</sub> cannot be used at higher pressures in colder environments because of its high boiling point.

The general high-voltage breakdown characteristics in compressed SF<sub>6</sub> gas are similar to other gases at high pressures and high fields (ref. 42). Certain salient facts concerning the breakdown of high-pressure SF<sub>6</sub> gas follow:

(1) At gas pressures of practical interest, values of the product  $pd$  are very high in most systems. In such cases the Paschen breakdown law is no longer satisfied. At high  $pd$  values, the breakdown voltages in compressed SF<sub>6</sub> are at fields far above 10 to 20 kV/mm. Reductions in breakdown voltage may be the result of electrode imperfections, dust, or particles. These factors create local high field areas where electrons can create electron avalanches and lead to streamer-initiated breakdown. Impurities and particulates must be avoided. They lower the breakdown strength of SF<sub>6</sub> (refs. 39, 40, 59, and 60).

(2) Breakdown voltage can be increased through repeated low-energy breakdowns, known as spark conditioning, or through increasing the voltage very slowly in steps, known as stress conditioning. Conditioning may result when high-field sites on the electrode surfaces (such as protrusion, dust, or particles) are progressively destroyed or when entrapped particles are moved into low-field regions where they cannot initiate breakdown.

(3) Electrode materials and surface preparation have a significant effect on the breakdown voltage, which increases with better electrode finish. The reduction in breakdown voltage from the theoretical "intrinsic" level is a function of the

product of the pressure  $p$  and height  $h$  of the electrode imperfection. Deviations begin for  $ph \geq 4$  kPa mm.

Therefore, electrodes should be made of hardened materials with polished, nonporous surfaces. Dielectric coating of electrodes increases the breakdown voltage in gases as compared with bare electrodes (ref. 60). Surface coating of electrodes will enhance equipment reliability if coating materials with long operational life are used. However, prolonged testing is required to develop such materials. These materials must not deteriorate or separate from the electrodes during the life of the power system.

Finally, the breakdown voltage in SF<sub>6</sub> decreases with increasing electrode area for both rough and smooth electrodes. This is related to the extreme value breakdown distribution of initiation by "weak points" on the electrode surface.

The gas breakdown characteristics of compressed SF<sub>6</sub> in uniform or near-uniform field geometry are fairly insensitive to small additions of dry air or nitrogen. A 20 percent addition of air by volume lowers the gas breakdown voltage by less than 5 percent. Small quantities of dry air (< 2 percent) are not considered damaging (refs. 42 and 61).

A 50 vol % SF<sub>6</sub>/50 vol % N<sub>2</sub> mixture has been proposed for saving costs in terrestrial systems. Its breakdown strength is only about 15 percent lower than pure SF<sub>6</sub> (ref. 62). This mixture would have the same strength as pure SF<sub>6</sub> if the pressure was raised by 10 percent.

For space use, mixing SF<sub>6</sub> with other suitable gases, such as N<sub>2</sub>, may be attractive if the insulated device must operate at low temperatures. Although SF<sub>6</sub> is relatively expensive, its excellent dielectric properties outweigh this concern.

As an added security to the system's reliability, high-voltage parts or modules submerged in SF<sub>6</sub> will reduce the probability of partial discharges or arcs inside the solid dielectric material, prolonging the life of the module (ref. 63).

In the light of its overwhelming advantages, pure pressurized SF<sub>6</sub> is the most suitable choice for future high-voltage applications in aerospace.

## Conclusions

Long-term projections for space activity envision a substantial increase in both the space-borne system power requirements and the mission durations. The need for higher voltages in space communication and power systems requires a critical evaluation of dielectric materials to ensure reliable and efficient mission operation. A review of the merits of solid, liquid, space vacuum, and gaseous dielectrics reveals that liquids are the most unlikely candidates for space applications. Exposed electrical systems in space vacuum will be susceptible to electric flashovers and breakdown because of (among others) the presence of fine particulates, contamina-

tion due to a variety of gases and ions, and plasma activity. Solid insulation will be massive, adding to system weight, and more difficult to manufacture without voids or cavities. In addition, thermal stresses can crack solid insulation and, hence, reduce system reliability.

Compressed-gas insulation, in general, and sulfur hexafluoride ( $\text{SF}_6$ ), in particular, offers the most viable alternative.  $\text{SF}_6$  is electronegative, is chemically stable, has very high dielectric strength, and is being used in high-voltage compact power systems on Earth. It is relatively insensitive to small quantities of gaseous contaminants and is self healing in the case of a momentary flashover or spark. The volume of a high-voltage power system insulated by compressed  $\text{SF}_6$  gas is substantially smaller, reducing weight. The pressure vessel will have a shielding effect and will suppress degassing of the system components. Because the pressure vessel is susceptible to gas leakage, an additional gas container will have to be provided on board the spacecraft, adding some weight.

Lewis Research Center  
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Cleveland, Ohio, April 11, 1995

## Appendix—Symbols

$C_1$	constant
$d$	distance between anode and cathode
$dx$	additional distance
$E$	electric field intensity
$E_{av}$	average electric field intensity
$E_{max}$	maximum electric field intensity
$e^{\alpha d}$	number of electrons produced by one electron in traveling the distance from the cathode to the anode
$h$	height of the electrode imperfection
$I$	current at the anode
$I_0$	electron current starting at the cathode
$I_{01}$	initial saturation current
$K$	ionization coefficient as a function of field strength and gas pressure
$K_1$	constant
$n$	number of electrons arriving at distance $x$ per second
$n_a$	number of electrons reaching the anode per second
$n_0$	number of primary electrons generated at the cathode per second

$n_+$	number of electrons released from the cathode by positive ion bombardment
$n_-$	number of negative ions
$p$	gas pressure
$R_1, R_2$	radii of curvature of the highly stressed electrode in two mutually orthogonal directions
$u$	field utilization factor
$V_b$	breakdown voltage of a uniform field gap
$V_s$	voltage at which sparking occurs
$V_1$	first applied voltage
$V_2$	second applied voltage
$V_3$	third applied voltage
$x$	distance from the cathode in the field direction
$x_c$	critical avalanche length, distance between the highly stressed electrode and the point in the electrode gap where $\alpha = \eta$
$\alpha$	Townsend's first ionization coefficient
$\bar{\alpha}$	$\alpha - \eta$ , effective ionization coefficient
$\alpha/p$	ionization coefficient
$\beta$	constant, $27 \text{ kV}^{-1}$
$\gamma$	number of electrons released from the cathode per incident ion, secondary ionization coefficient
$\eta$	attachment coefficient, number of attachments produced in the path of a single electron traveling a unit distance in the direction of the electric field

### Subscripts:

max	maximum
min	minimum

### Superscript:

*	unstable ion
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